भारतीय प्रौद्योगिकी संस्थान (भारतीय खनि विद्यापीठ) धनबाद

IIT ISM

INDIAN INSTITUTE OF TECHNOLOGY (INDIAN SCHOOL OF MINES) DHANBAD

GPC510 - Well logging

Semester - Winter 2024; Lecture - 18

Partha Pratim Mandal
Assistant Professor
Department of Applied Geophysics
E: partham@iitism.ac.in / partha87presi@gmail.com

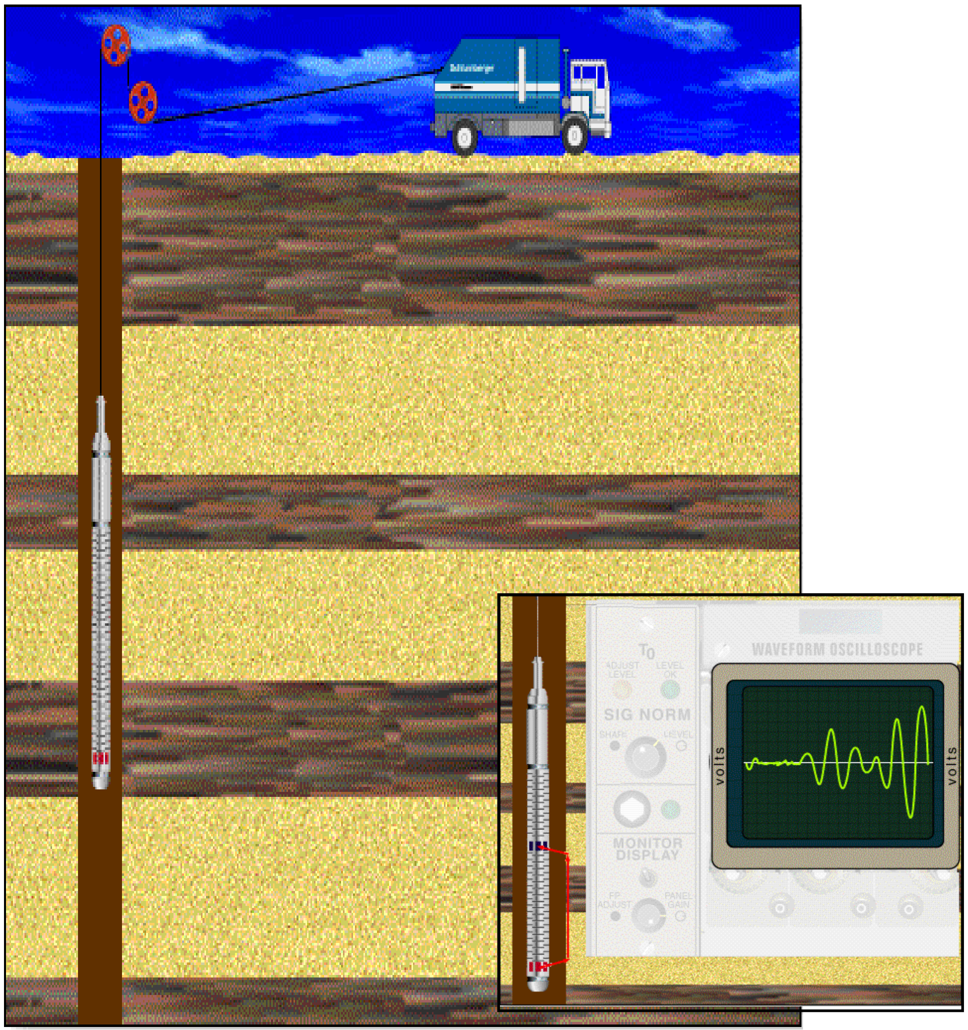
AGENDA

- Introduction
- Principles of acoustic waveform
- Tool design
- Influencing factors
- Porosity calculation
- Ratio plot
- Sonic & Seismic
- Cement bond logging & Application

INTRODUCTION

- Sonic log records the **speed of sound waves** in a borehole, and it is also known as an acoustic log
- The sonic log data is displayed as interval transit time, abbreviated to DT, Δt (delta t)
- DT is a measure of slowness; the inverse of the velocity of the sound wave
- The interval transit time at subsurface formation depends upon lithology and porosity
- Porosity dependence of the log, makes it a useful tool of porosity estimation

THEORY

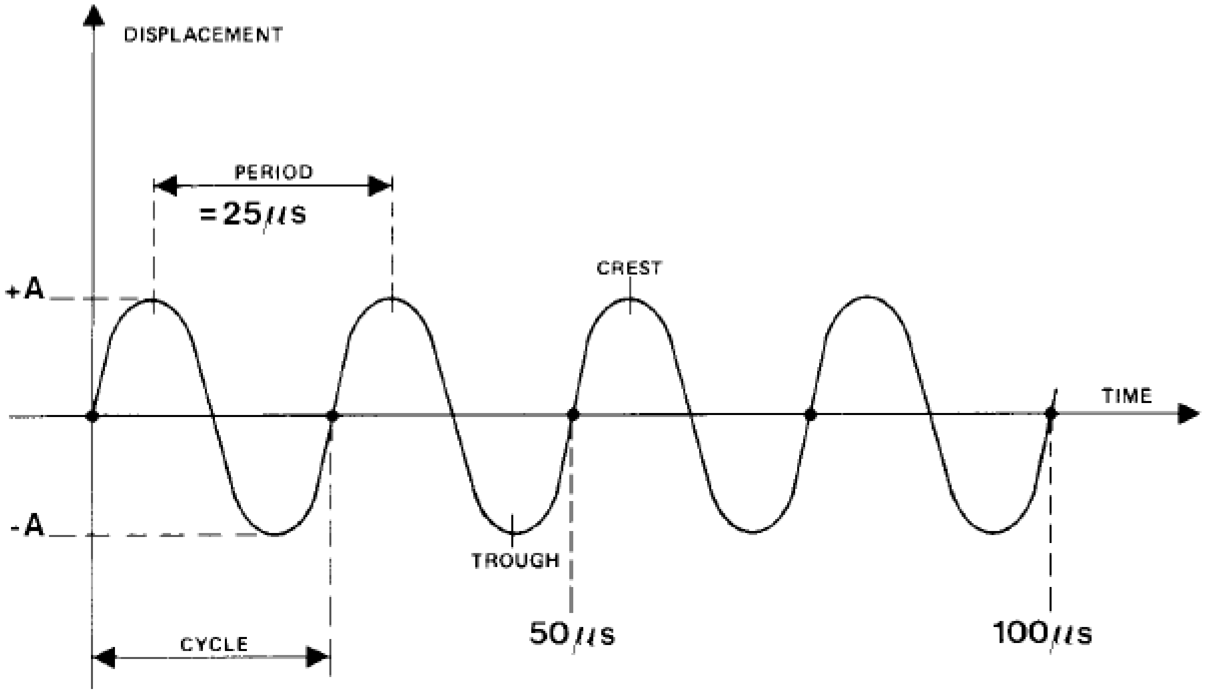


- Sonic Tools are based on the measurement of the travel times and amplitudes of the body waves in the rocks
- **Applications:**
  - Mechanical properties :
    - Rock strength, Earth stress
    - Rock Mechanical Properties
    - Rock failure mechanisms
  - Formation evaluation
  - Elastic properties
  - Cement bond logging

(Crains Petrophysical Handbook, 2000; Rider, 1996)

ACOUSTIC SIGNAL

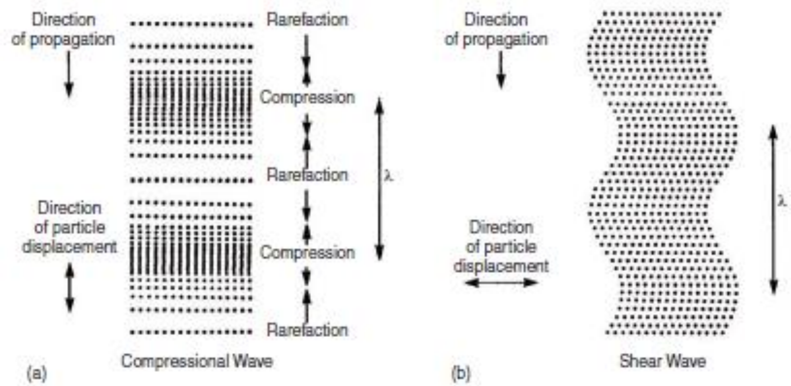
- Period, T
- Frequency, f
- Wavelength, λ = v/f



WAVEFORMS

Two types of sound waves propagated in an infinite medium

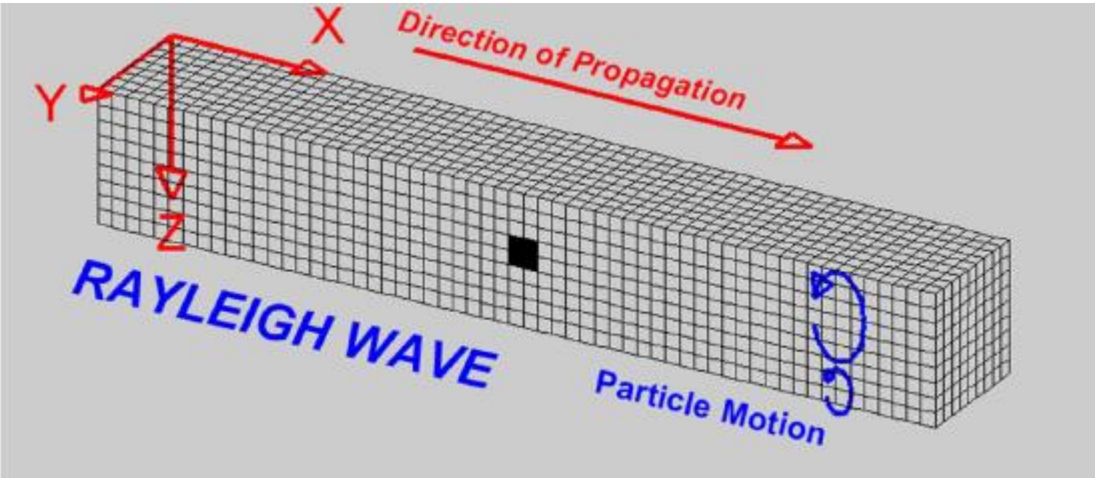
- Compressional waves (**P-waves**): direction of wave propagation parallel to the direction of particle displacement, can propagate all kinds of medium (gases, liquids and solids). Fastest wave
- Shear waves (**S-waves**): direction of wave propagation perpendicular to the direction of particle displacement, can only propagate through solids. Next to fastest
- Shear wave can not propagate through fluids and slower than P-waves



WAVEFORMS

Other waves or interface waves include:

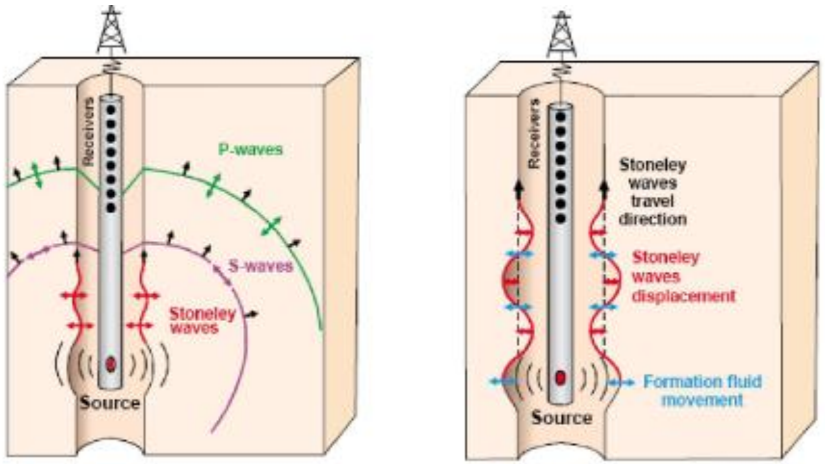
- **Rayleigh waves**: occur at the mud/formation interface, combination of two displacements, one parallel with and the other perpendicular to the interface. Speed is roughly 0.9 times of shear wave velocity.



WAVEFORMS

Other waves or interface waves include:

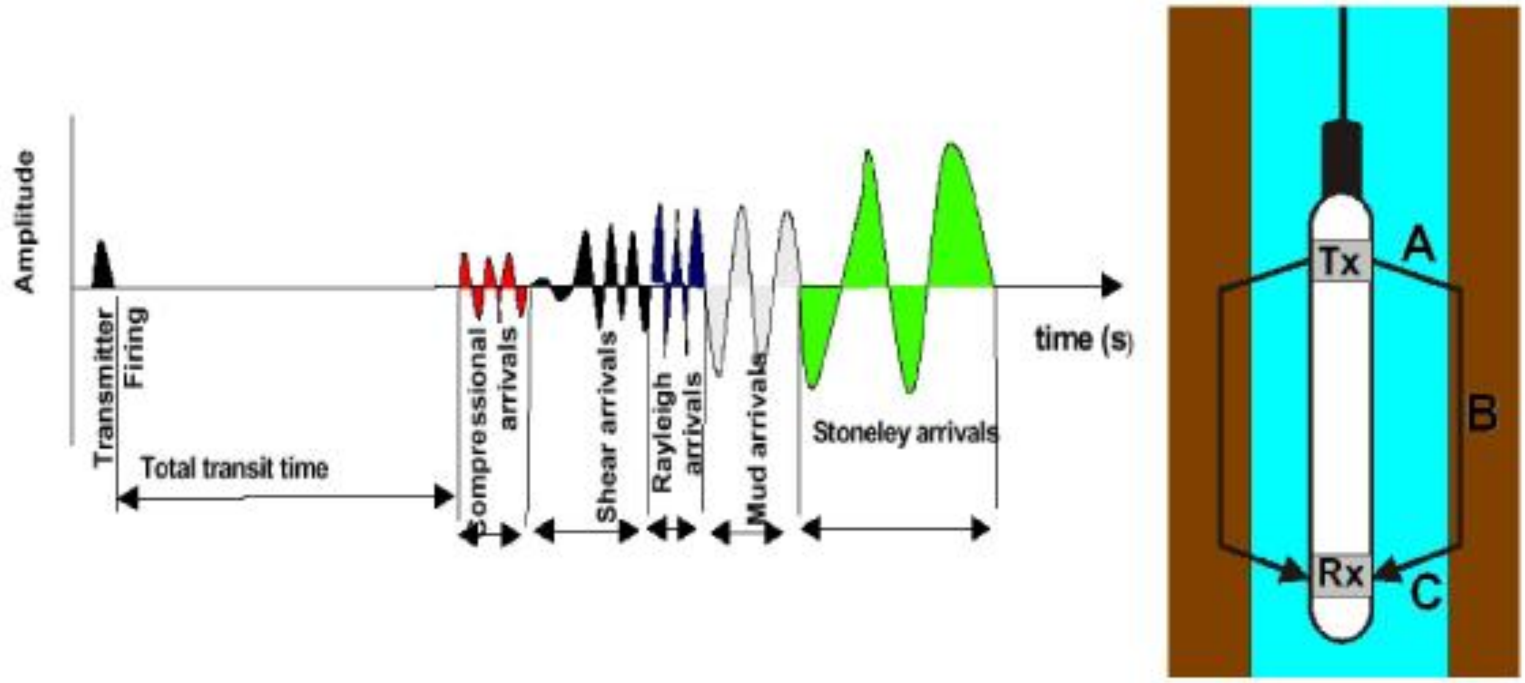
- **Stoneley waves**: travel in mud by interaction between mud and the formation. Their amplitude decays exponentially, in both mud and formation away from borehole boundary. These low-frequency waves are called tube waves. Its value is lower than mud compressional-wave velocity



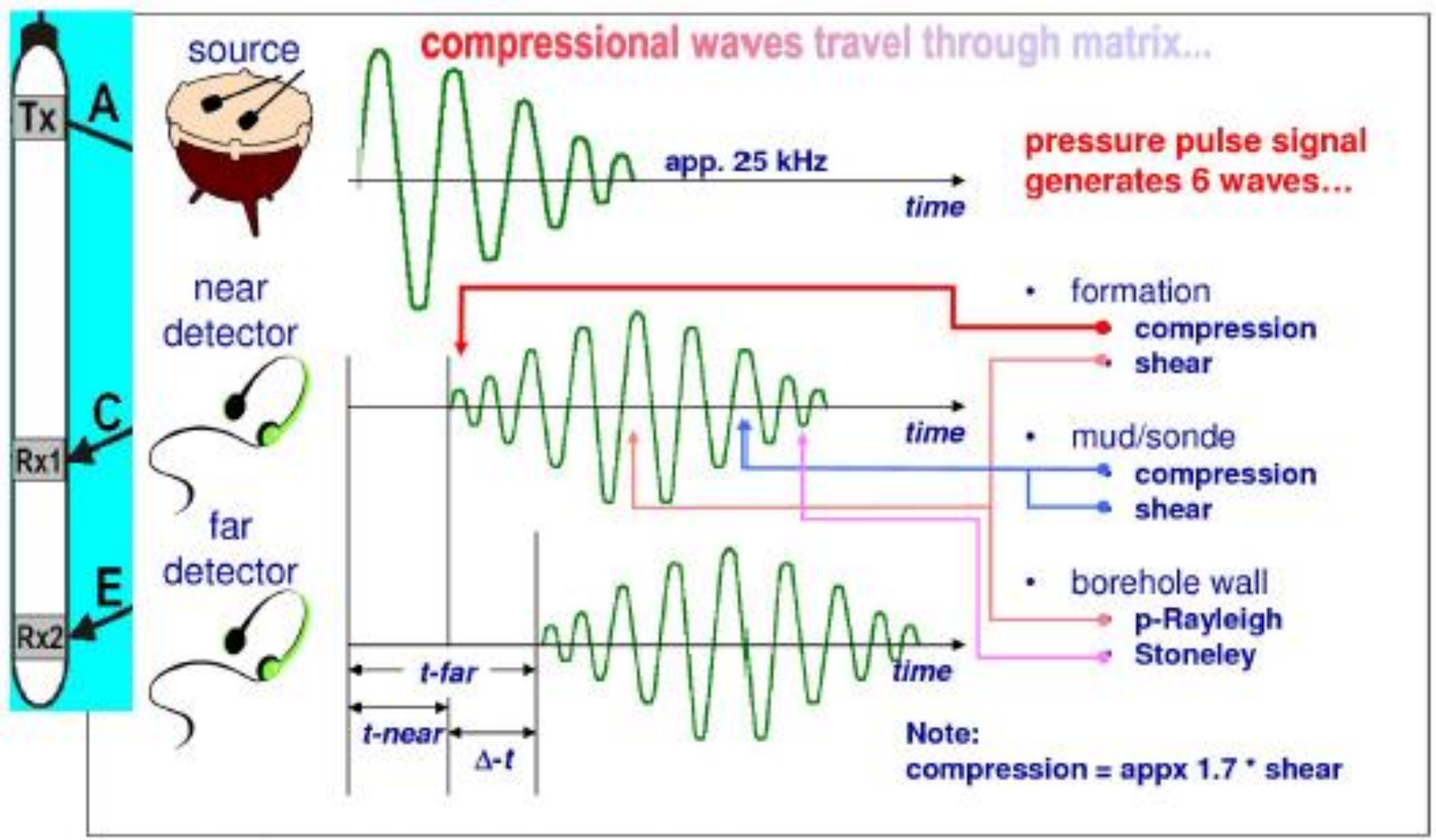
Borehole acoustic waves (left) wave types generated by a monopole of a logging tool; (right) Stoneley waves propagate along the borehole wall and their velocity is always less than that of the borehole fluid velocity. Note that they are essentially expanding/ contracting borehole waves and that their motion is axially symmetrical.

WAVEFORMS

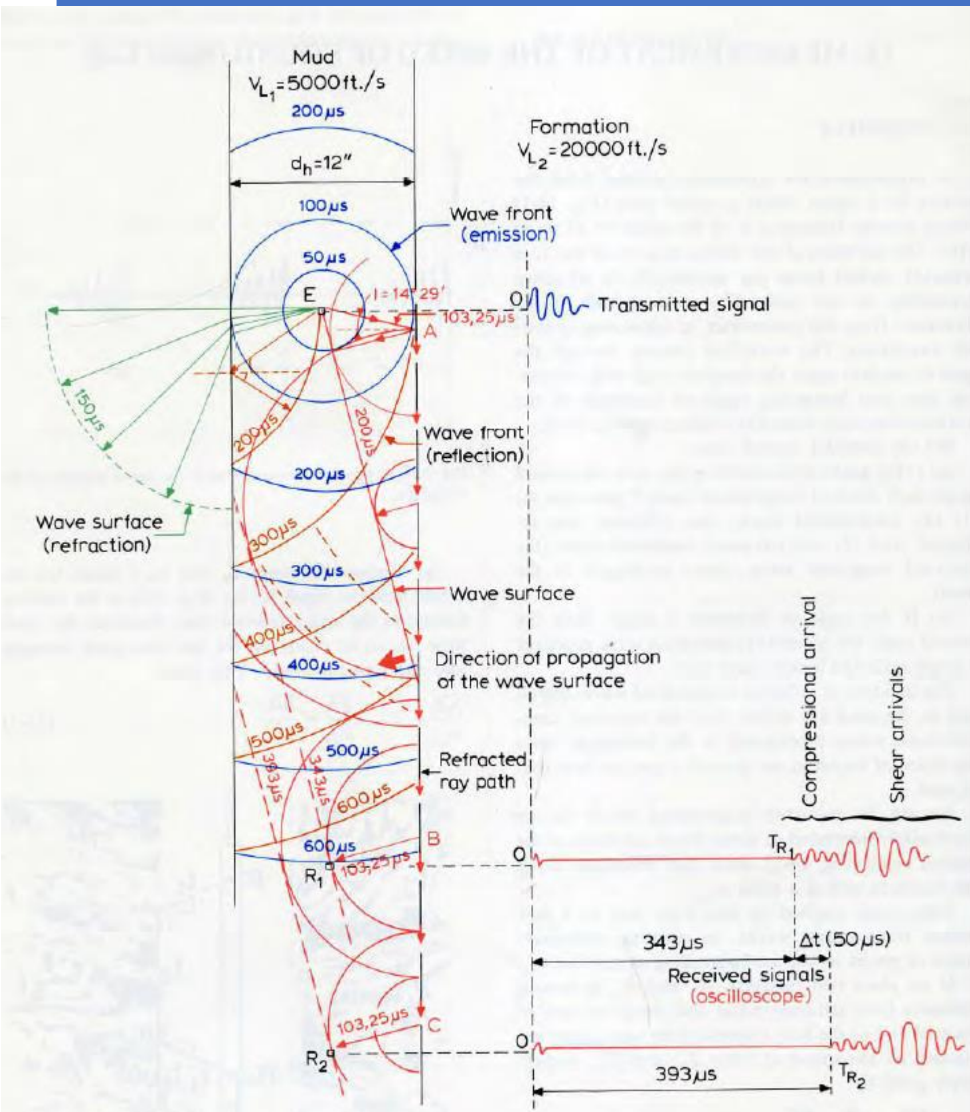
Typical borehole acoustic waveforms for one pulse as recorded in receiver



WAVEFORMS & SONIC MEASUREMENTS



ACOUSTIC WAVE PROPAGATION



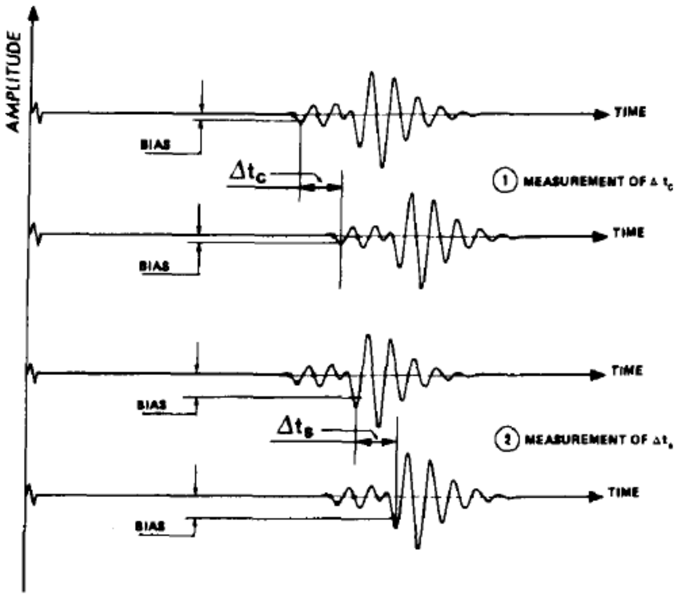
- A transducer emits a sound wave with average frequency range **20 to 40 kHz**
- Wave spreads in all direction, generating spherical wavefronts
- The wavefront passes through the mud and then incident upon borehole with increasing time and increasing angle as distance increases
- Two scenarios can be considered

First: if angle of incidence is less than critical angle – the compressional wave gives rise to (i) two compressional waves - one reflected and one refracted (ii) one refracted transverse wave

Second: if angle of incidence is greater than critical angle, the incident wave produces a single reflected compressional wave

COMPRESSIONAL WAVE ARRIVAL

- Measurement of the first wave arrival relates only to those waves refracted at the critical angle as these are the fastest.
- Other longitudinal waves refracted into the formation travel at same speed as the first arrival but arrive later due to their long path length (example green refracted wave in previous slide picture)
- Transverse waves refracted into the formation travel more slowly than the longitudinal wave and therefore arrives as later waves. However, their energy is higher , therefore can be easily seen on the oscilloscope. Detection of refracted shear arrival requires higher threshold of wave detection than to compressional arrivals



EARLY SONIC TOOLS

- Had one transmitter or source (T_x) that emits a sound pulse and one receiver (R_x) that picks up and records the pulse passing the receiver. Wave pulses generated by the transmitter travels through the mud (A), formation (B) and mud again (C).
- Body made from rubber to stop waves travelling through the tool to the receiver (Rx)
- Two main problems with this tool
  - Measured travel time was too long (mud travel time i.e., A+B+C rather than B)
  - Formation travel distance (B) was not constant in the case of caving or tool tilting

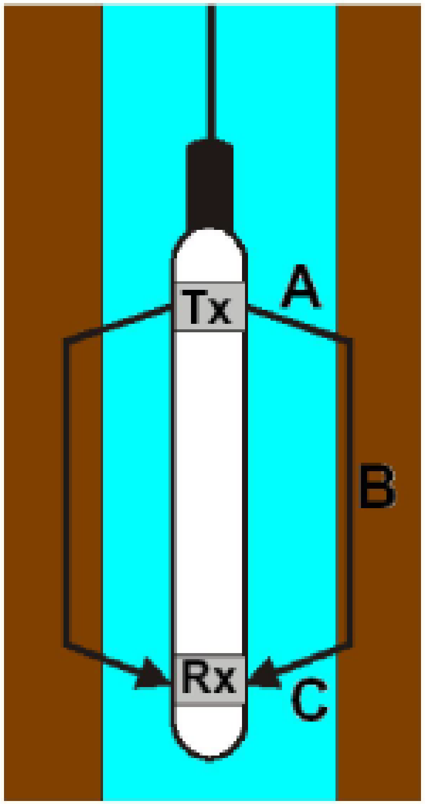


Illustration of early sonic tool

DUAL RECEIVER TOOLS

- 1 transmitter and 2 receivers
- Two receivers are short distance apart, measure the difference in arrival times of elastic waves

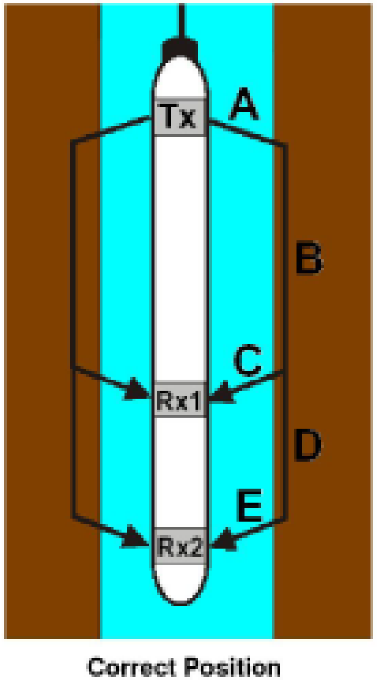
Time to Rec1 (Rx1) = A +B+C

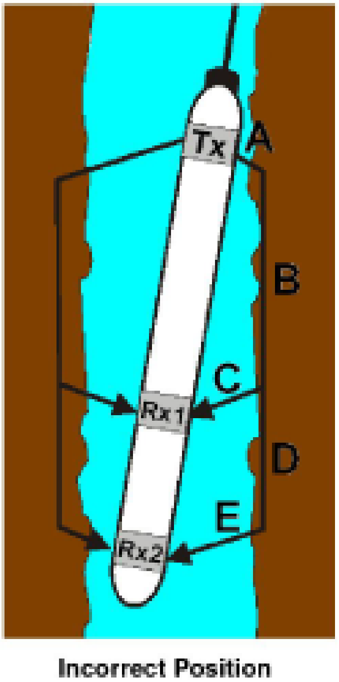
Time to Rec2 (Rx2) = A +B+D+E

- Therefore, the sonic interval transit time,

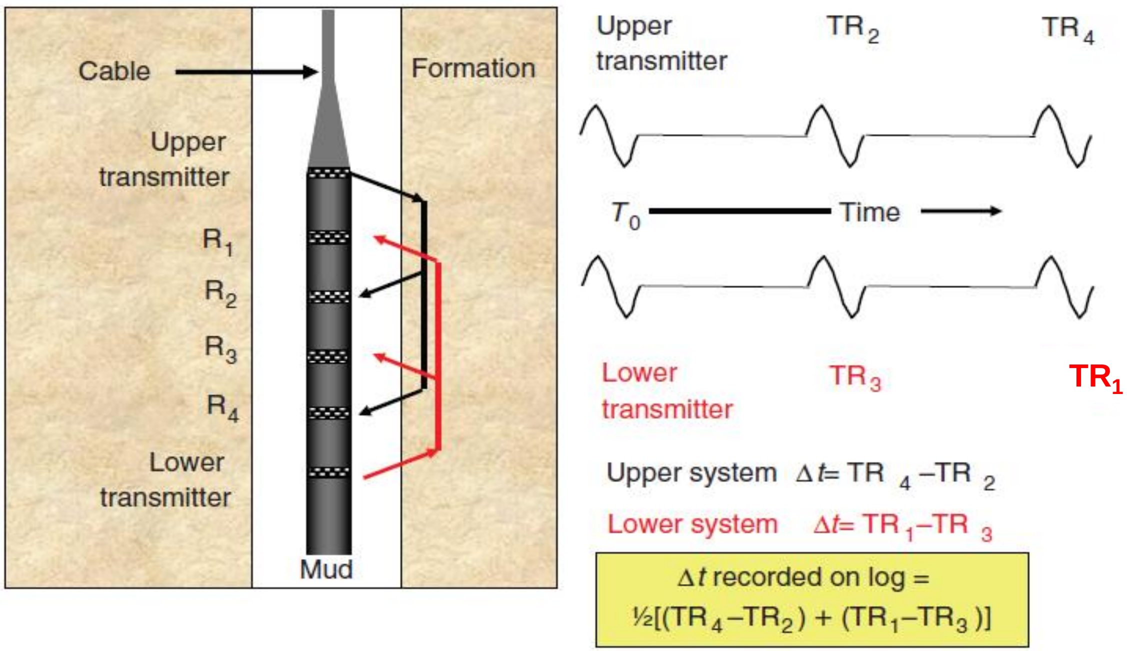
DT = A+B+D+E – (A+B+C) = D+E-C

- If tool is axial in borehole, then C =E. Hence DT = travel time of D
- Problem if tilted (or bad hole) as C # E and the dual receiver tool do not work properly





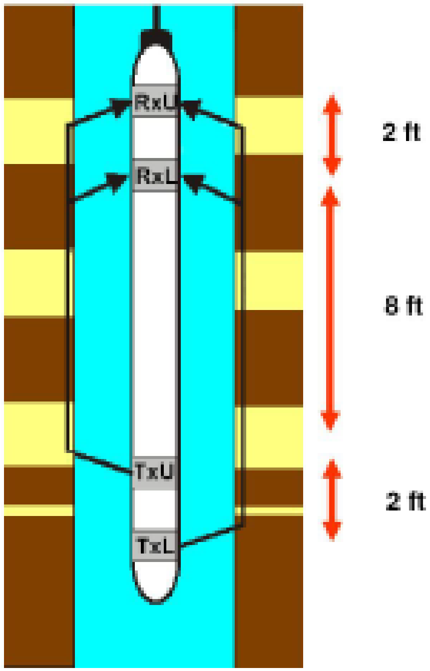
BOREHOLE COMPENSATED TOOL



- Designed to automatically compensate for tool misalignment and some hole size variation
- Two transmitter and four receivers.
- Transmitters pulsed alternatively, and DT values calculated from alternate pairs of receivers. The two values of DT are averaged to compensate for tool misalignment
- Tx-Rx distances typically 3 and 5ft. Rx-Rx distance is 2ft
- Typically, 20 pulses/sec and logging speed ~5000ft/hr

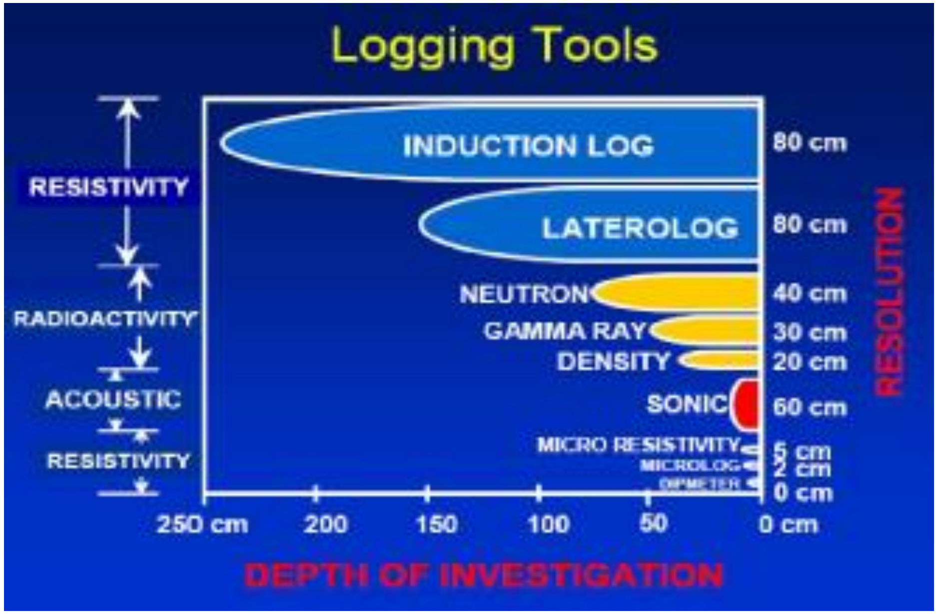
LONG SPACING TOOL

- Developed to overcome severely bad hole as long spaced tools theoretically have greater chance of detecting compressional waves from undamaged formation
- Schlumberger's long spacing sonic (LSS) tool contains 2 transmitter s(upper and lower) 2ft apart and 2 receivers (upper and lower), 2 ft apart
- Pairs of receivers and transmitters are 8ft apart
- Tool records 2 readings, a near reading with a 8-10ft spacing and a far reading with a 10-12 ft spacing
- 25cm depth of investigation



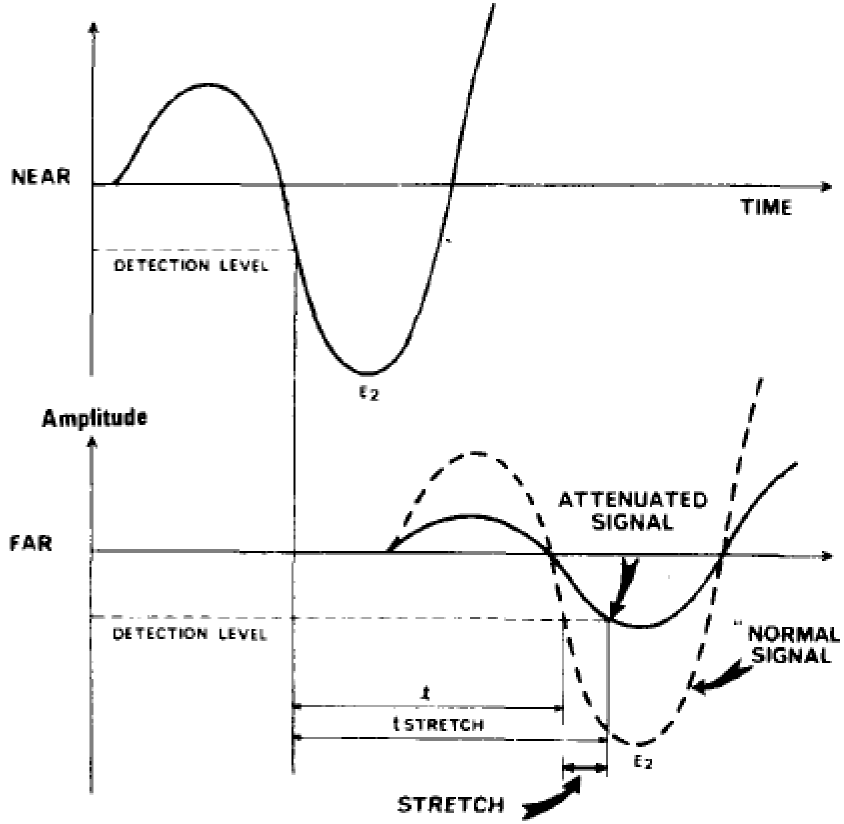
DEPTH OF INVESTIGATION & RESOLUTION

- Compressional waves created by transmitter do not penetrate deeply
- Reach around 2.5 – 25 cm depth and move along the borehole wall
- Max resolution of about 0.5 - 0.6 m for a qualitative measurement is possible

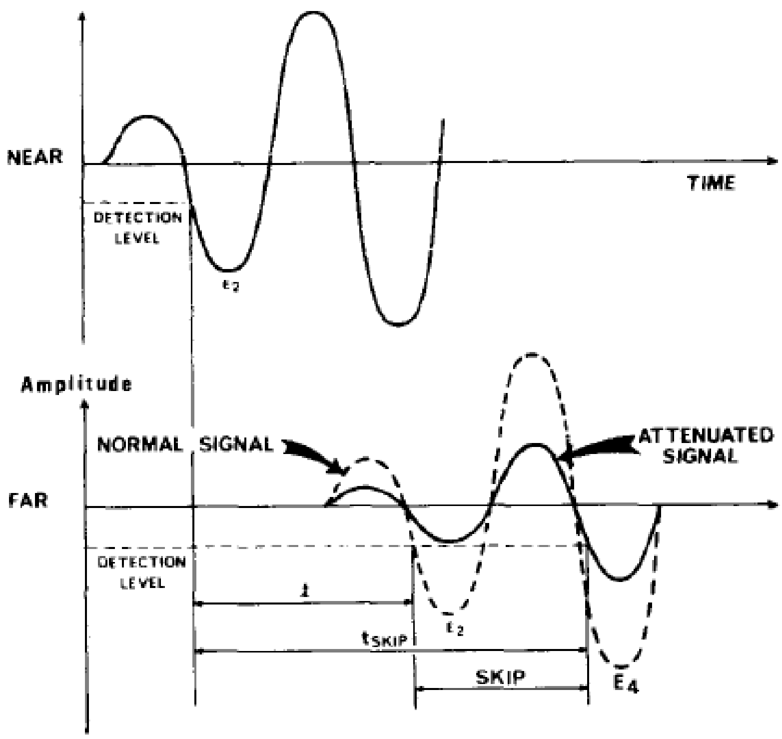


TIME STRETCH & CYCLE SKIPPING

Time stretch

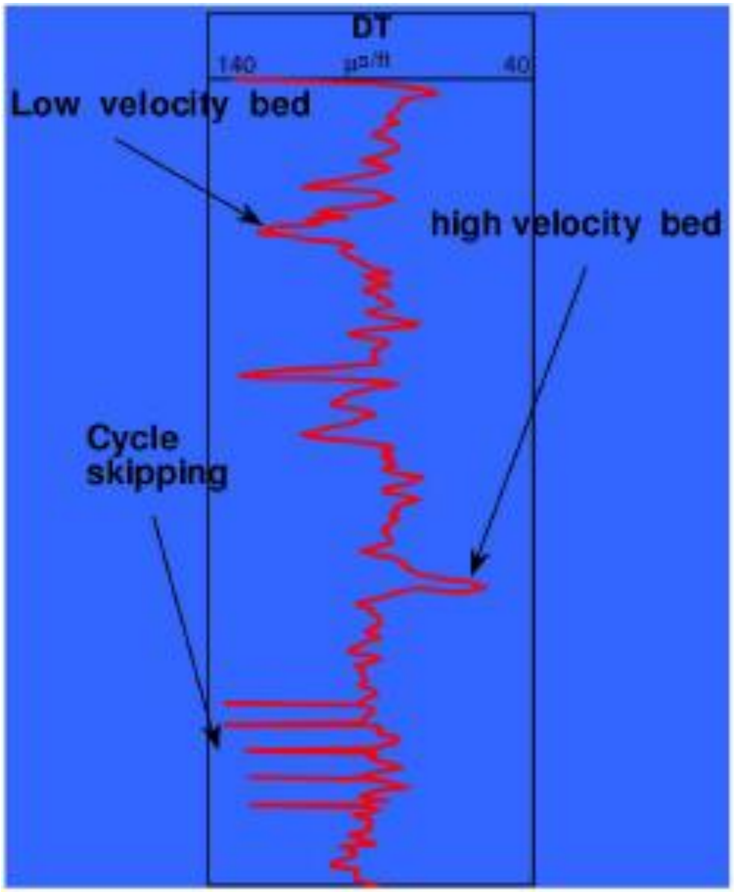


Cycle skipping



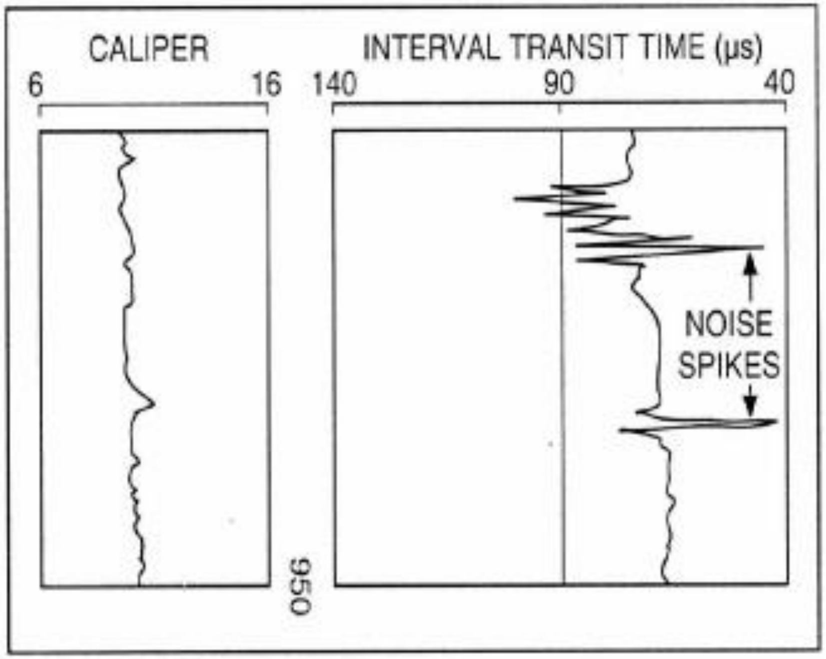
SONIC LOG DISPLAY

- 140 - 40 us/ft standard scale for compressional wave while for shear wave scale can be 440 to 40 us/ft
- Cycle skipping can happen due to poor borehole condition and the hole is severely caved and enlarged. Also occurs in gas bearing zones
- Cycle skipping occurs when sound waves from the source reach first receiver but are too low to reach and trigger the far receiver



NOISE SPIKE

- Occurs with extreme bad hole, and rugose holes
- In gas bearing zones



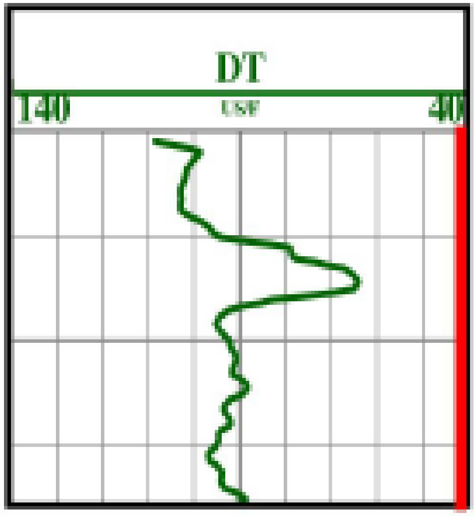
Example of noise spikes on the sonic log. Most noise spikes are toward lower transit time

ACOUSTIC VELOCITY

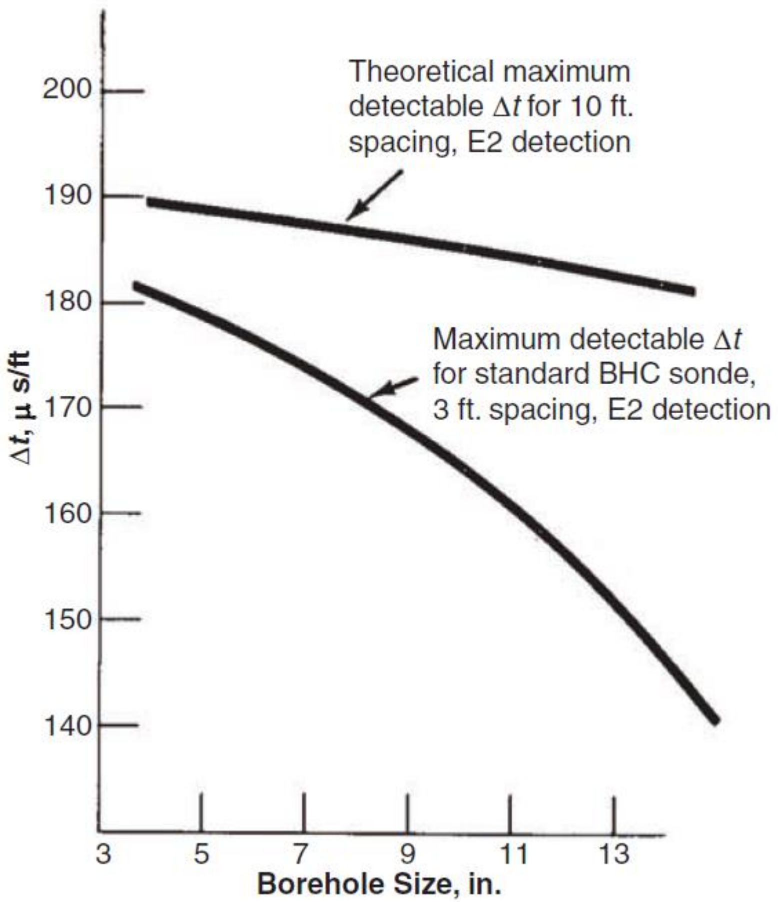
- Sonic logs are reported in microseconds (10-6 seconds)per foot
- This is called interval transit time (DT) usual range 40-140 us/ft
- Velocity is the reciprocal of sonic transit time

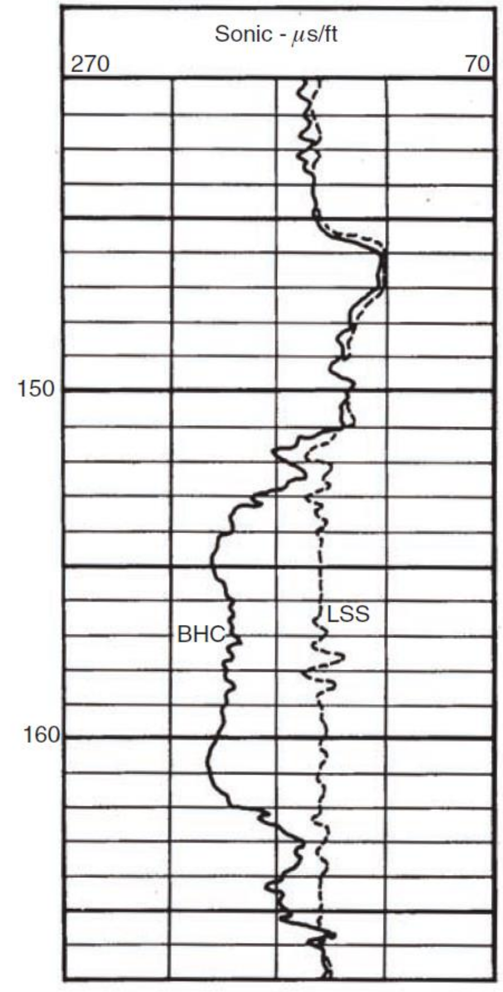
$$Velocity = \frac{1}{DT\ x\ 10^{-6}} \text{ ft/s}$$

= 304800/DT m/s

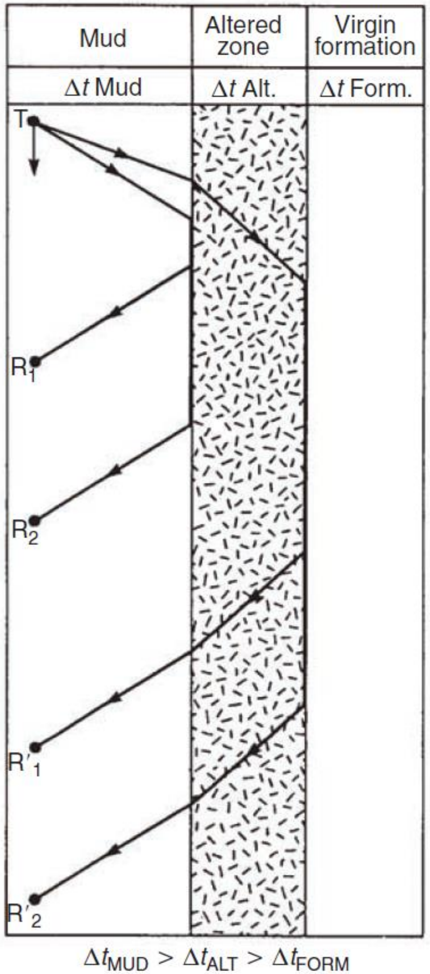


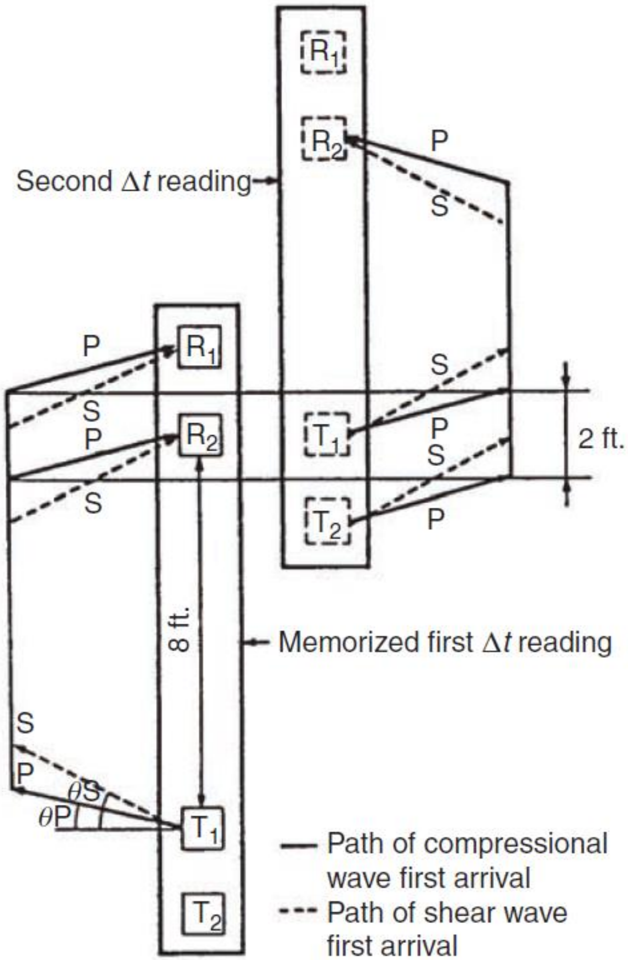
BOREHOLE SIZE – BHC VS LSS





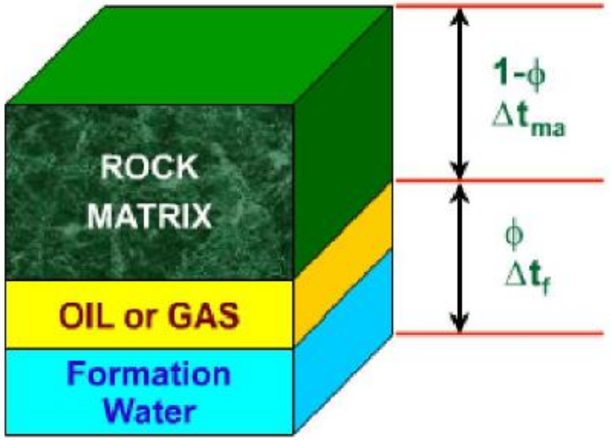
SHORT AND LONG SPACING





SONIC POROSITY CALCULATION

Porosity can be calculated from the sonic log, but this calculation is usually inferior to neutron or density log calculations



Wyllie's time average equation

$$\Delta t_{LOG} = \phi \Delta t_f + (1 - \phi)\Delta t_{ma}$$

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}}$$

Where

ϕ = porosity

Δt = interval transit time (tool measured)

Δtma = transit time of matrix material

Δtf = transit time of interstitial fluid

COMPACTION EFFECT

Unconsolidated formations exhibit longer time travel time than accounted by Wyllie time average. Conventional way to address :

$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta tf - \Delta t_{ma}} \times \frac{1}{B_{cp}}$$

Where B_{cp} = DT_{sh}/100

SONIC POROSITY CALCULATION

Raymer-Hunt Gardner (1980) Equation

Another method for calculating the porosity from the sonic log was proposed by Raymer et al. This is expressed as:

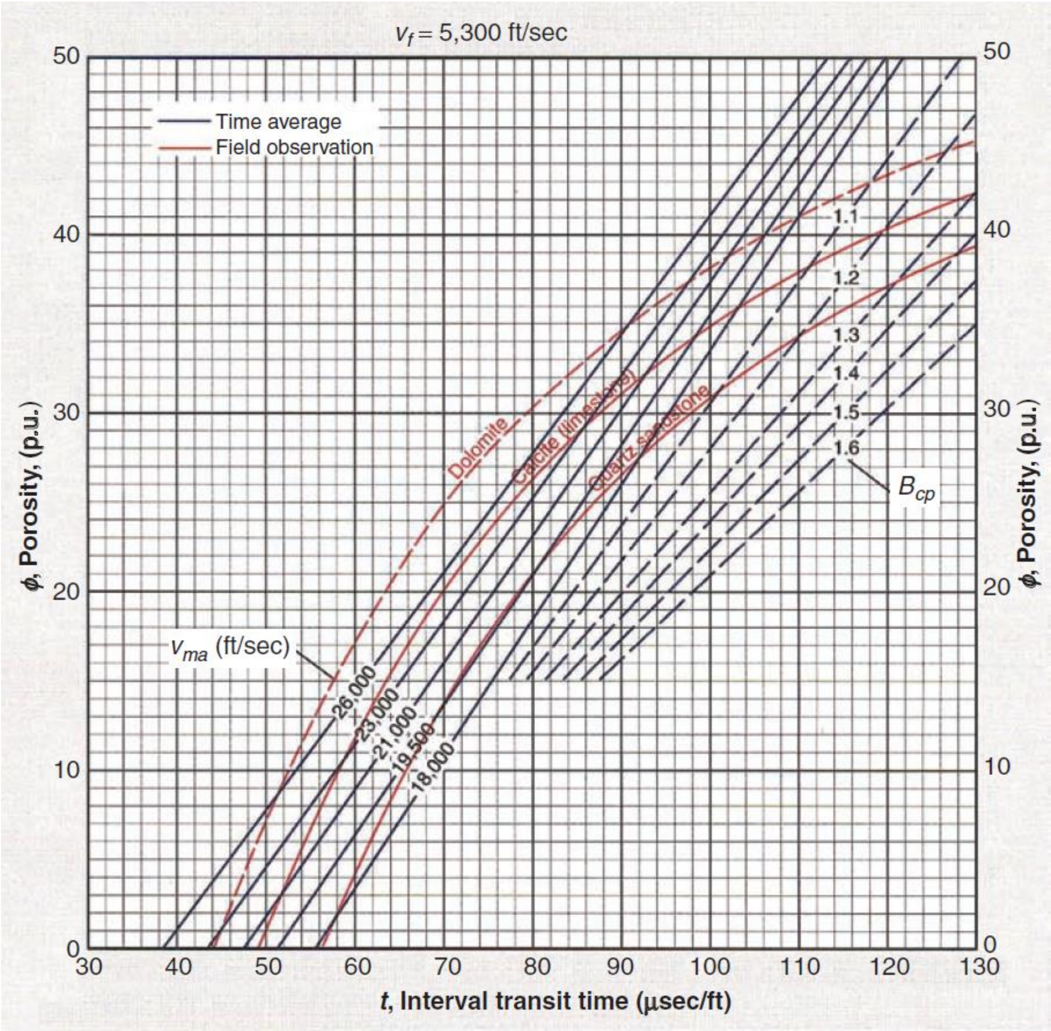
$$\frac{1}{\Delta t} = \frac{\phi}{\Delta t_f} + \frac{(1-\phi)^2}{\Delta t_{ma}}$$

Raymer et al., equation can be simplified as:

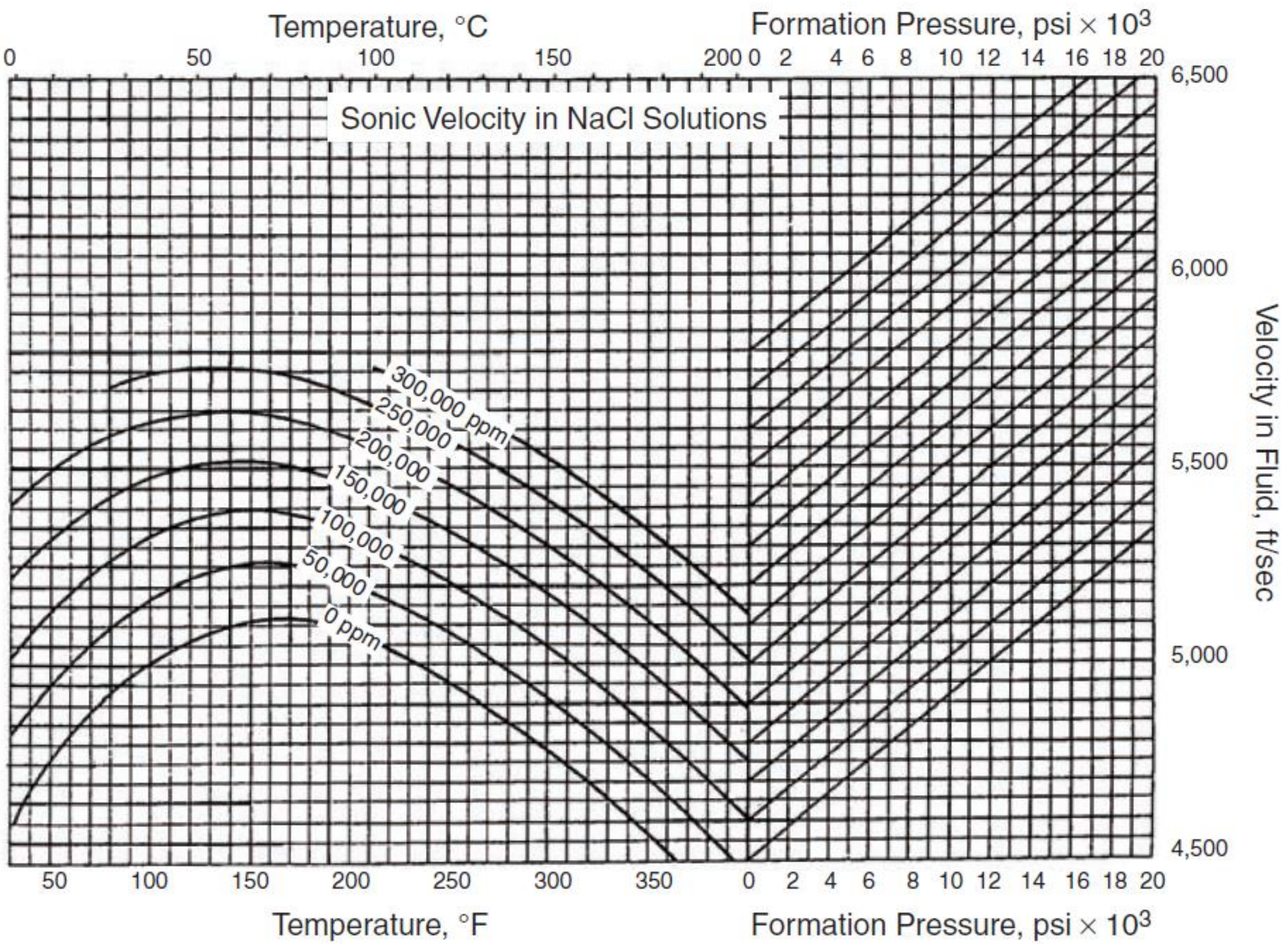
$$\phi = C\frac{\Delta t - \Delta t_{ma}}{\Delta t}$$

C varies from 0.625 to 0.7 for liquid filled reservoir and 0.6 for gas saturated intervals.

SONIC POROSITY

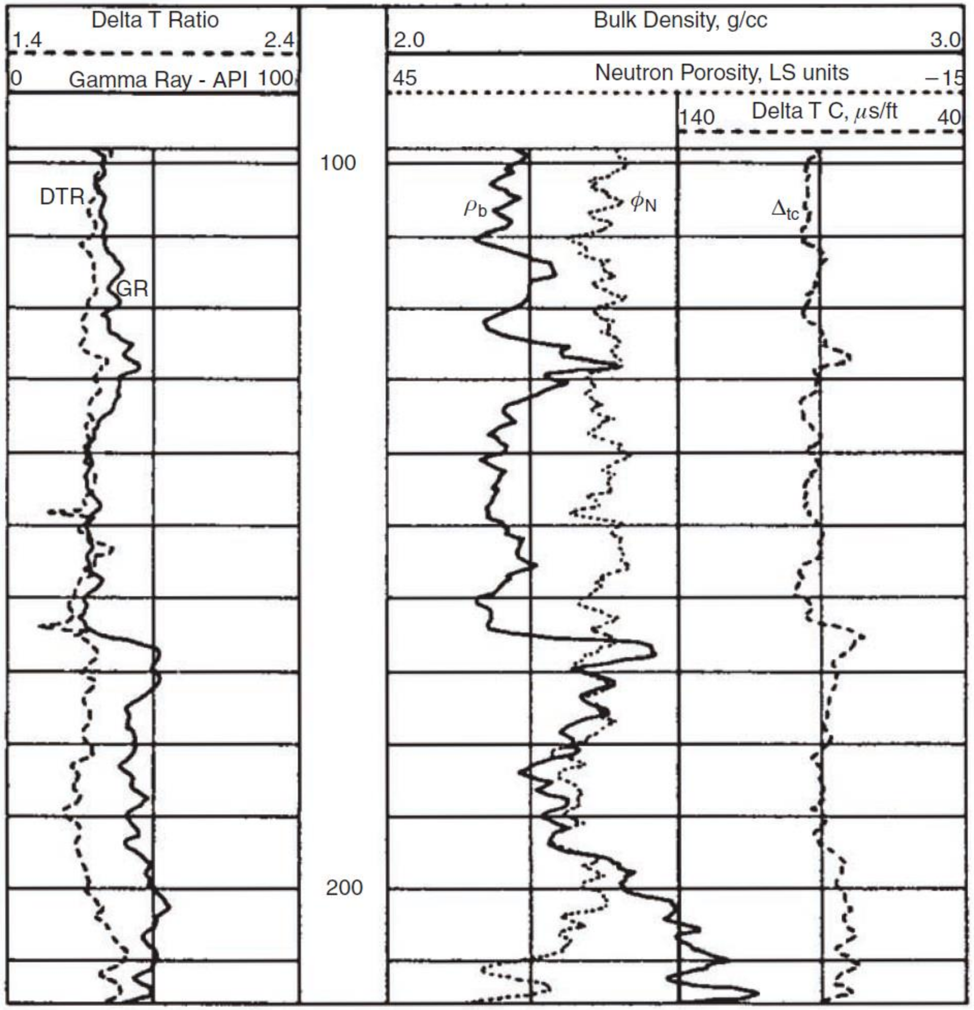


FLUID VELOCITY



Δt RATIO PLOT

- Ratio of $\Delta t_s / \Delta t_c$ a useful indicator formation evaluation i.e., lithology identification, formation fluid determination, and rock physics study
- Also called DTR log
- Ratio plot unaffected by mica or nonradioactive mineral like feldspar



Bateman, 2012

Δt RATIO PLOT

- If lithology is known, it is possible to derive Δt_s from the log readings of Δt_s and listed ratio from the supplied table

$$\Delta t_s = \Delta t_c * ratio$$

- Grain size also affected the ratio; therefore, correction is required.

TABLE 16.4—TRAVEL-TIME CORRECTION FACTOR α FOR GRAIN SIZE [AFTER MASON (1984)]

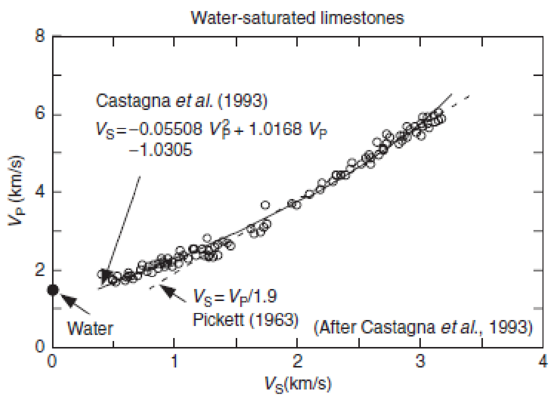
Wentworth's Classification	Grain Size (mm)	$\Delta t_s/\Delta t_c$ Correction Factor α
Silt	1/16	0.90
Very fine grained	1/16–1/8	0.95
Fine grained	1/8–1/4	1.00
Medium grained	1/4–1/2	1.05
Coarse grained	1/2–1.0	1.10
Very coarse grained	1.0–2.0	1.15
Granules	2.0–4.0	1.20
Granules	>4.0	>1.30

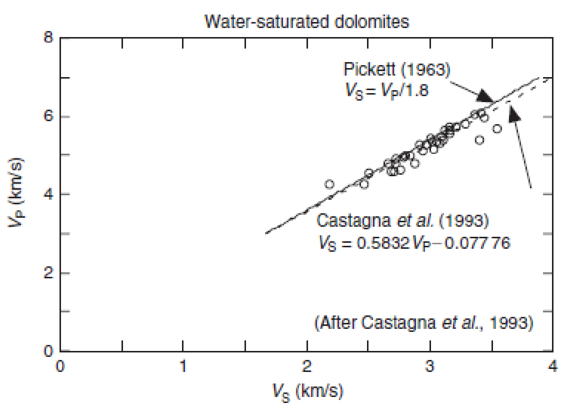
Bateman, 2012

TABLE 16.3—Δt RATIO FOR ROCK TYPES [AFTER MASON (1984)]

Formation Lithology	Ratio $\Delta t/\Delta t$
Anhydrite	2.45
Basalt	1.55
Chalk	2.45
Chert	1.6
Clay	3.2
Claystone	1.9
Diabase	1.7
Diorite	1.75
Dolomite	1.8
Epidosite	1.7
Gabbro	1.6
Gneiss	1.8
Granite	1.7
Gypsum	2.45
Hornstone	1.85
Limestone	1.9
Limestone (silty)	2.1
Limestone (argillaceous)	2.3
Marble	1.8
Mudstone	1.85
Pyrite	1.7
Quartz	1.55
Quartzite	1.5
Salt	2.15
Sandstone	1.6
Shale	1.7–1.75
Siltstone	1.8

EMPIRICAL APPROACH



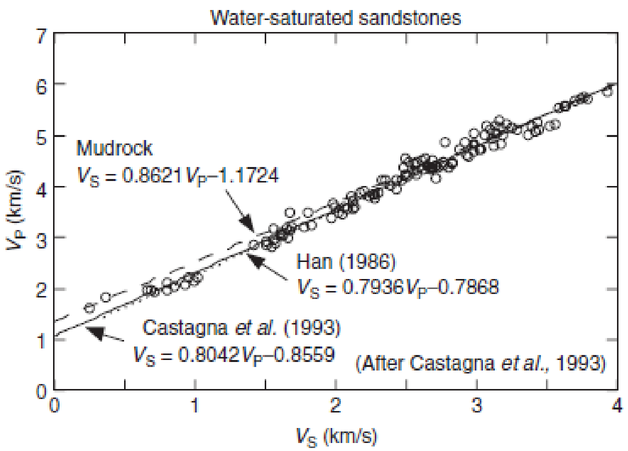


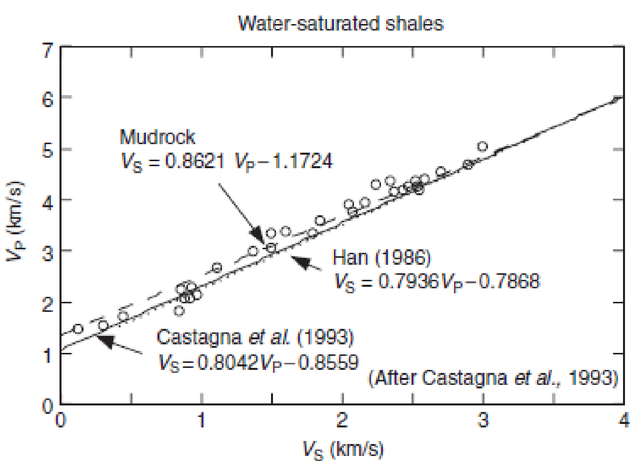
Limestone & Dolomite

Estimation of V_s from compressional velocity is a known well approach for seismic inversion and rock physic study

Mavko et al., 2009; Castagna et al., 1993

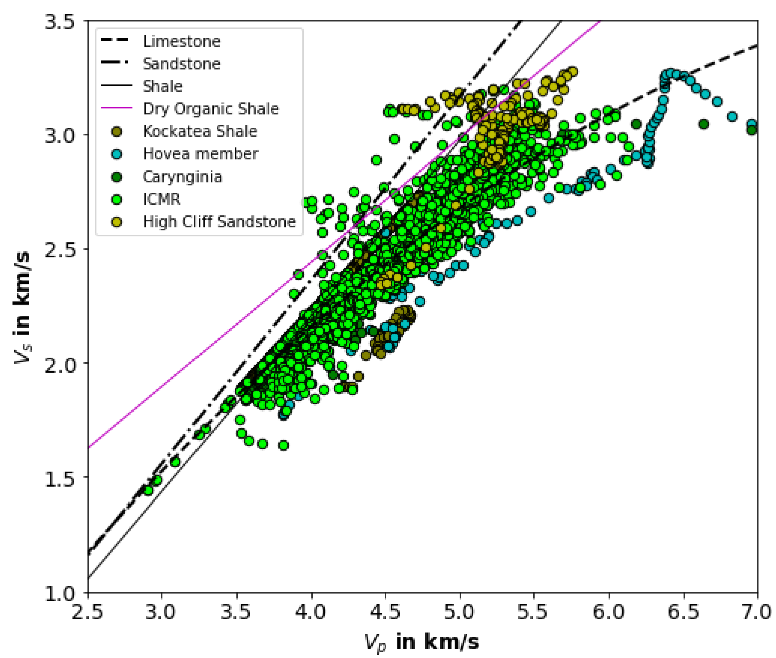
EMPIRICAL APPROACH





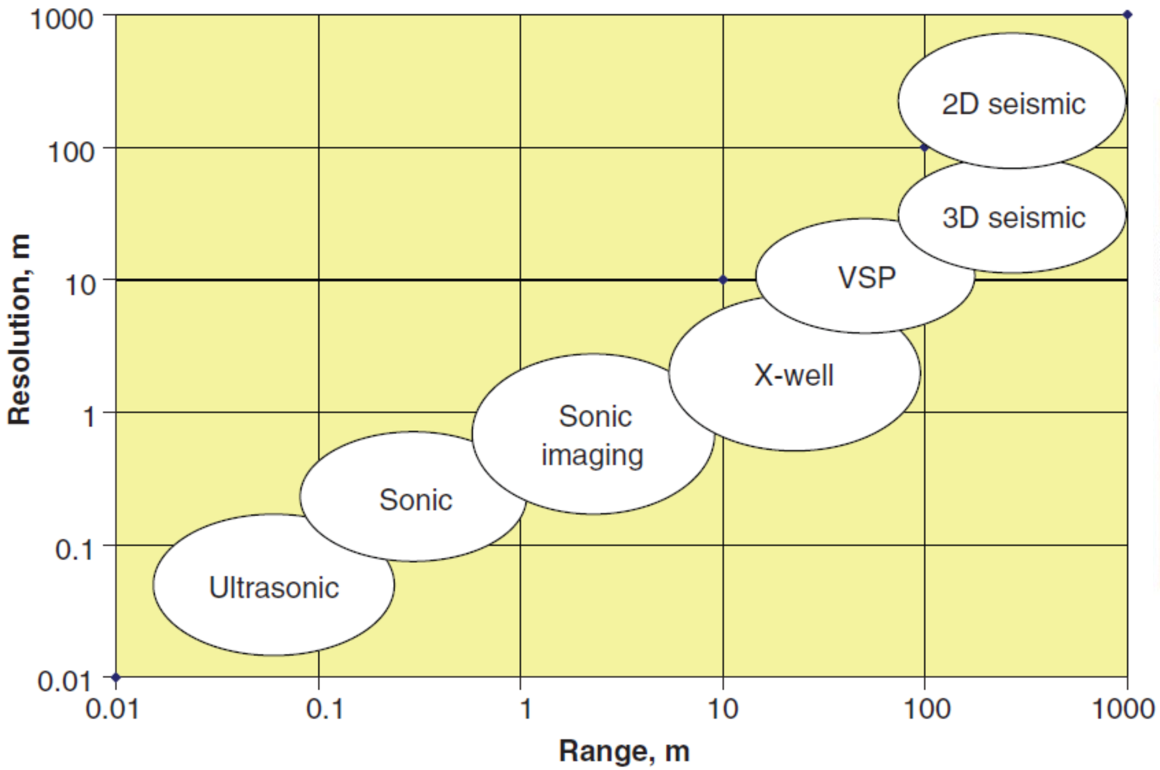
Sandstone & Shale

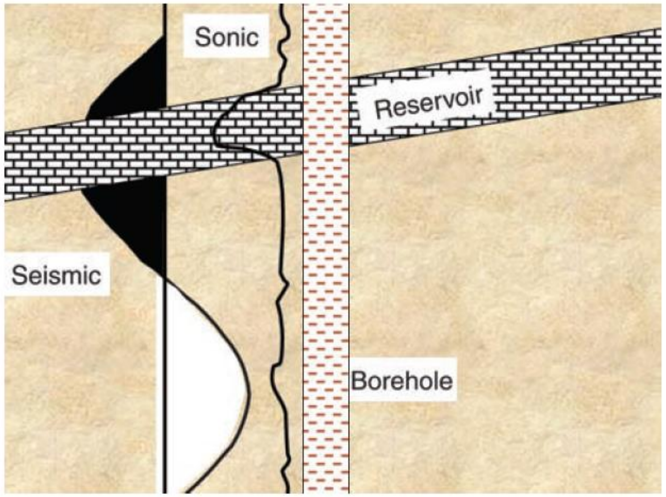
Estimation of V_s from compressional velocity is a known well approach for seismic inversion and rock physic study



Mandal et al., 2021; Mavko et al., 2009

RESOLUTION AND RANGE

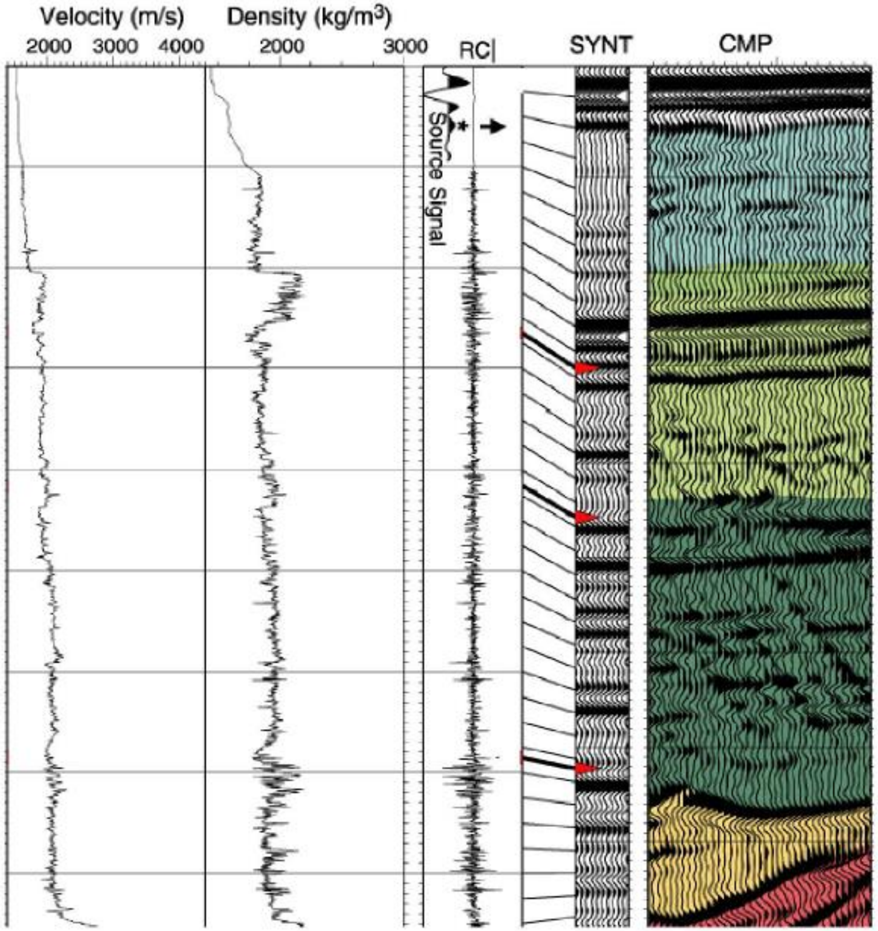




Bateman, 2012

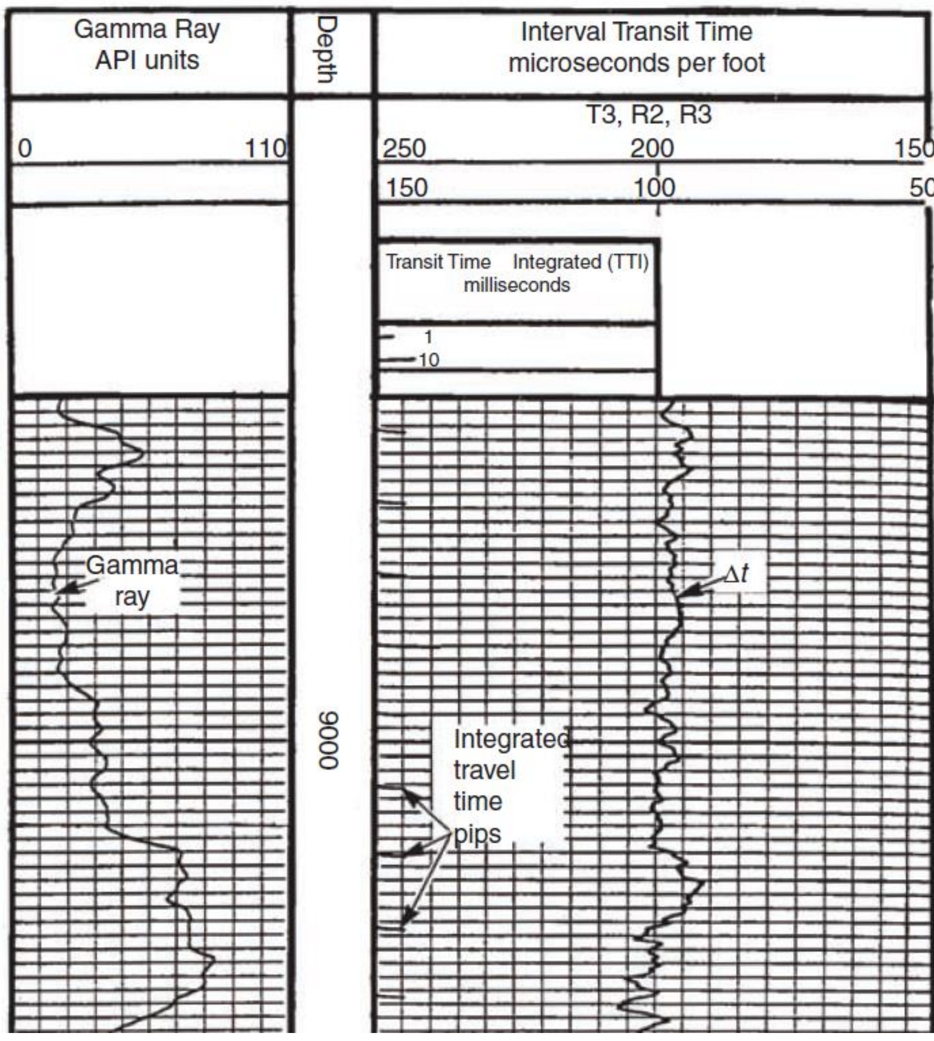
SONIC & SEISMIC

- Sonic logs are essential to integrate with seismic data
- Synthetic seismograms are generated from the sonic log and are upscaled to seismic scale
- Note: The resolution of the sonic log is about 2 ft (60 cm) whereas the resolution of seismic data ranges from 5 - 20 m
- $RC = \frac{Z_2 - Z_1}{Z_2 + Z_1}$, Z = ρV [ρ = density, V= velocity]



TRANSIT-TIME INTEGRATION

- Time-depth relationship of a particular geological column is required for proper seismic analysis
- Integrated travel-time are displayed as a series of time ticks
- Average travel times can be computed between two depth by counting those ticks



SONIC ATTENUATION

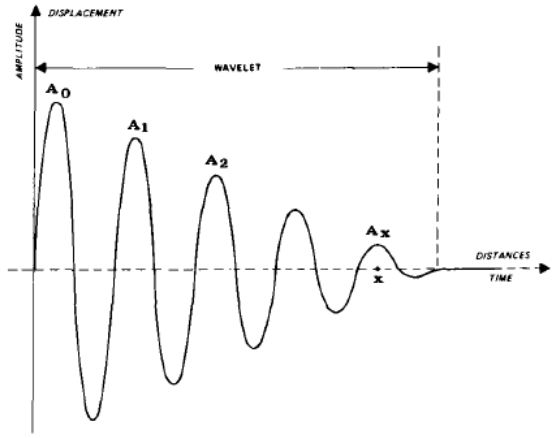
- Amplitude of acoustic wave decreases when it propagates through subsurface media – known as attenuation
- Attenuation at subsurface formations depends upon several factors:

(i) wavelength and type (compressional or shear)

(ii) Rock texture – pore and grain size, type of grain contact, grain distribution , porosity, permeability

(iii) Pore fluids and its viscosity

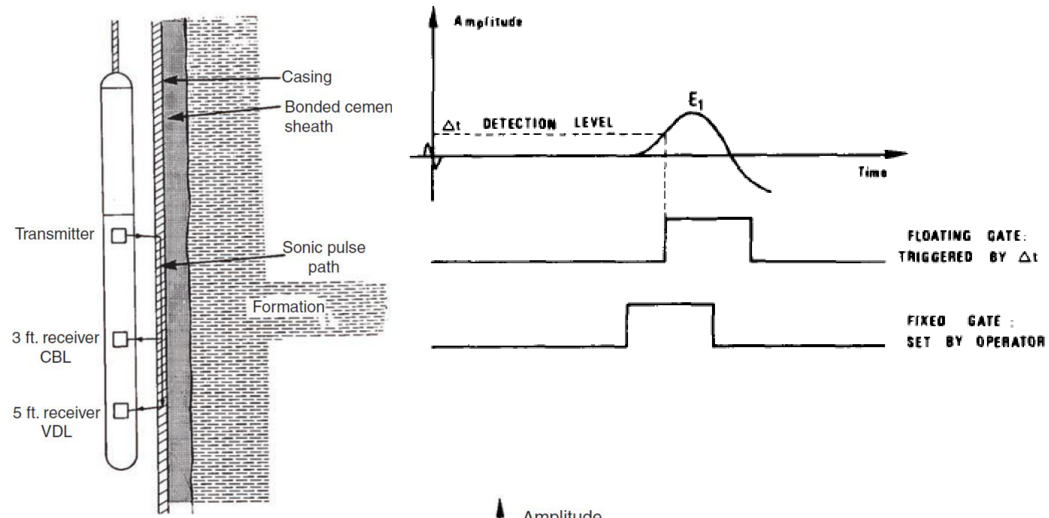
(iv) Presence of natural fractures

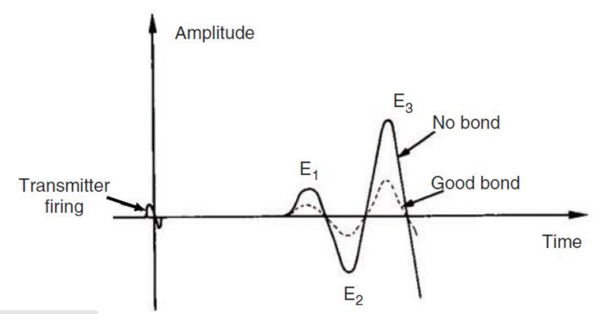


- For cased hole, the attenuation depends upon quality of cement around the casing. This is done through measurement of sonic amplitude, known as cement bond log

CEMENT BOND LOG (CBL)

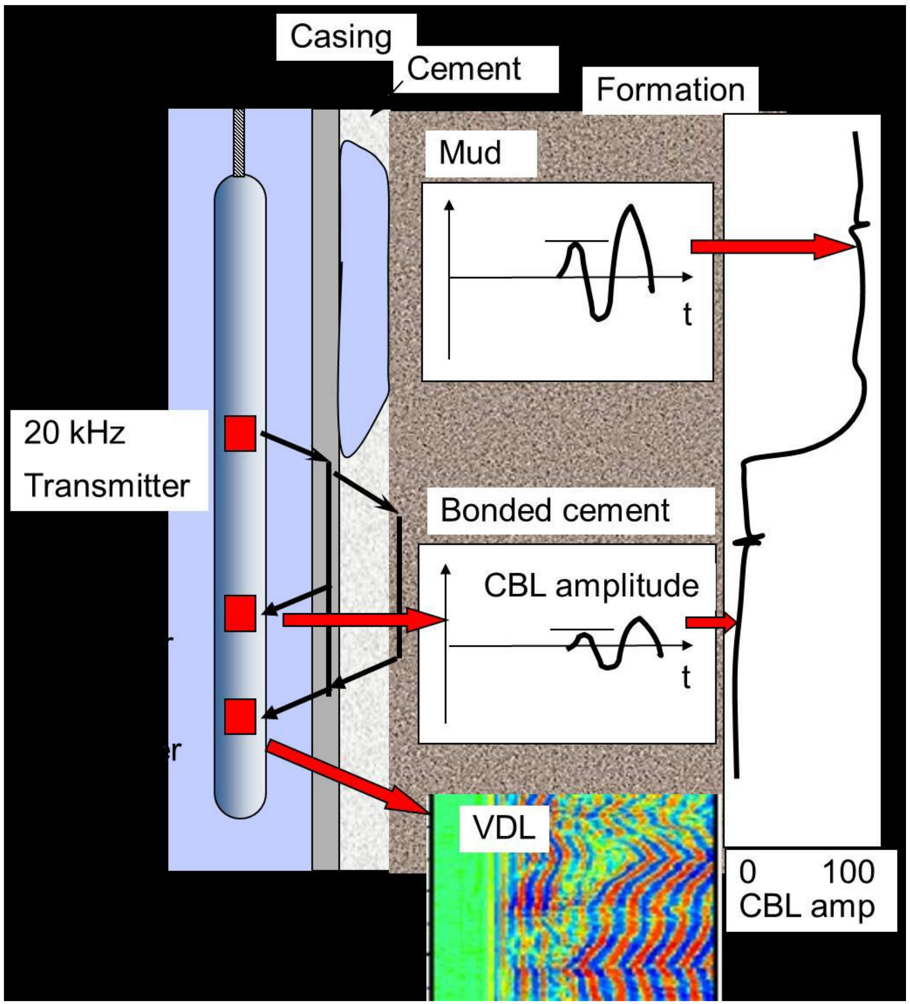
- CBL is recorded with a sonic tool equivalent to the design of the BHC. It records the amplitude of the first arrival
- These arrivals have frequency range of 20-25 kHz
- The amplitude is measured using an electronic gate (fixed or floating gate)
- Change in first arrival peak amplitude when good bonding exists between casing and formation
- Interpretation of CBL consists of determination of bond index – defined as ratio of attenuation in zone of interest to the maximum attenuation in a well cemented zone





Bateman, 2012

CBL/VDL PRINCIPAL



Haggag, M., 2024

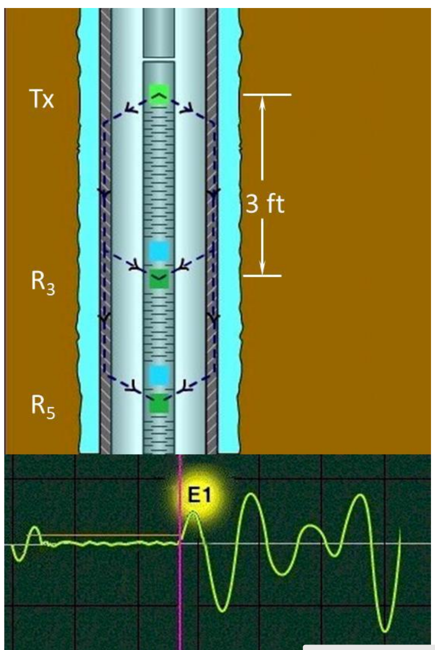
CEMENT BOND LOGGING APPLICATION

CBL: Cement Bond Log

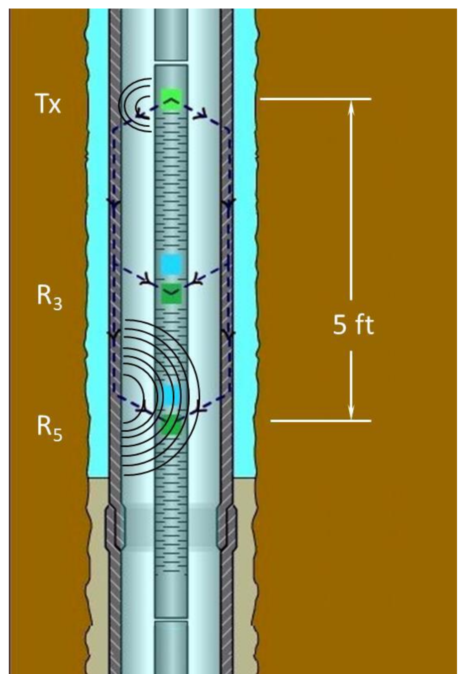
- **CBL is the amplitude of First Arrival in mV**
- **Measured at 3 ft Receiver**
- **It is a function of the Casing-Cement Bond**
- **TT : Transit Time is the time elapsedfromT0 to first Arrival, it is used as log quality control indicator**

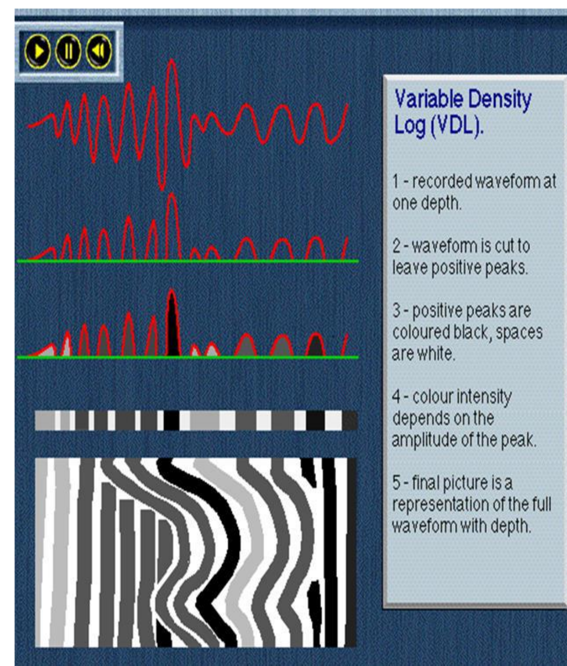
VDL: Cement Bond Log

- **5 ft Receiver for VDL analysis**
- **Allows easy differentiation between casing and formation arrivals**



Haggag, M., 2024



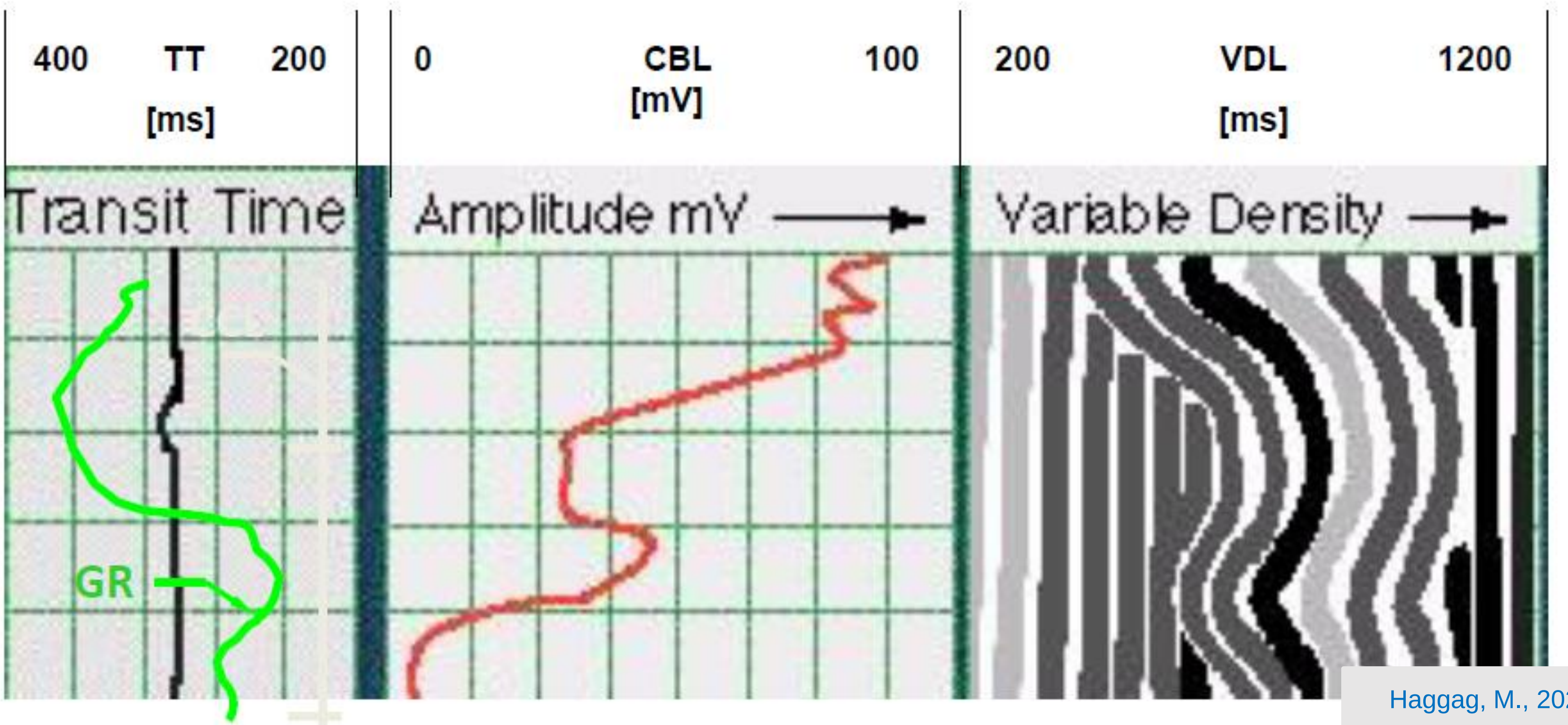


CEMENT BOND LOGGING APPLICATION

- **Evaluate zonal isolation**
  - **Zone to zone isolation**
  - **Casing-cement isolation**
  - **Cement-formation bond**
- **Cement distribution behind casing to ensure corrosion protection.**
- **Identify top of cement**
- **Evaluate cement remedial jobs**

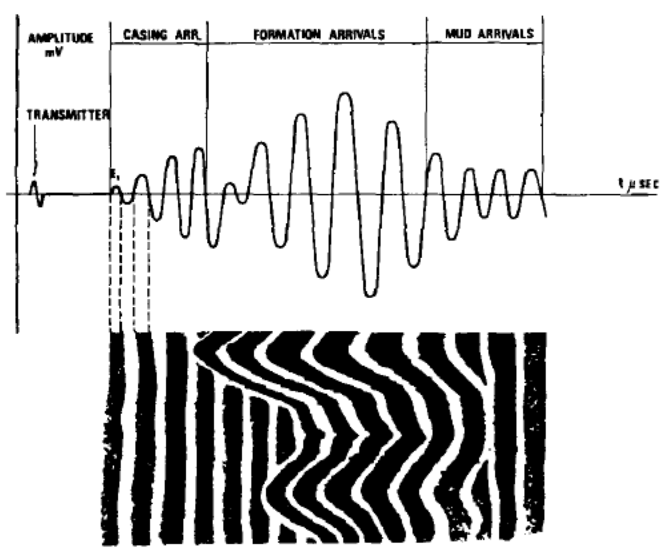
CBL/VDL LOG PRESENTATION

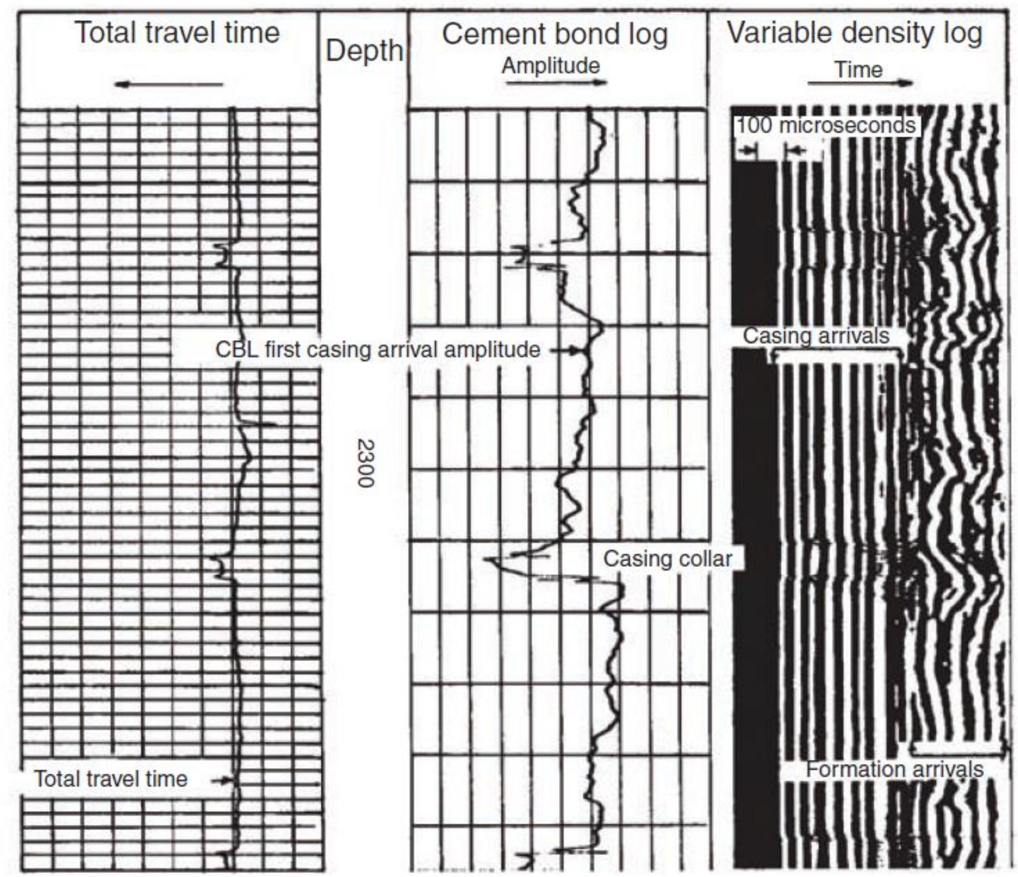
- **Transit Time TT in micro-seconds ms**
- **CBL Amplitude in millivolts mV**
- **VDL Variable Density Log [waveform visual representation]**



VARIABLE DENSITY LOG (VDL)

- How do you check the bonding quality?
- Created a wave train visible as variable density log (VDL)
- Height of the positive half waves of the sonic signal





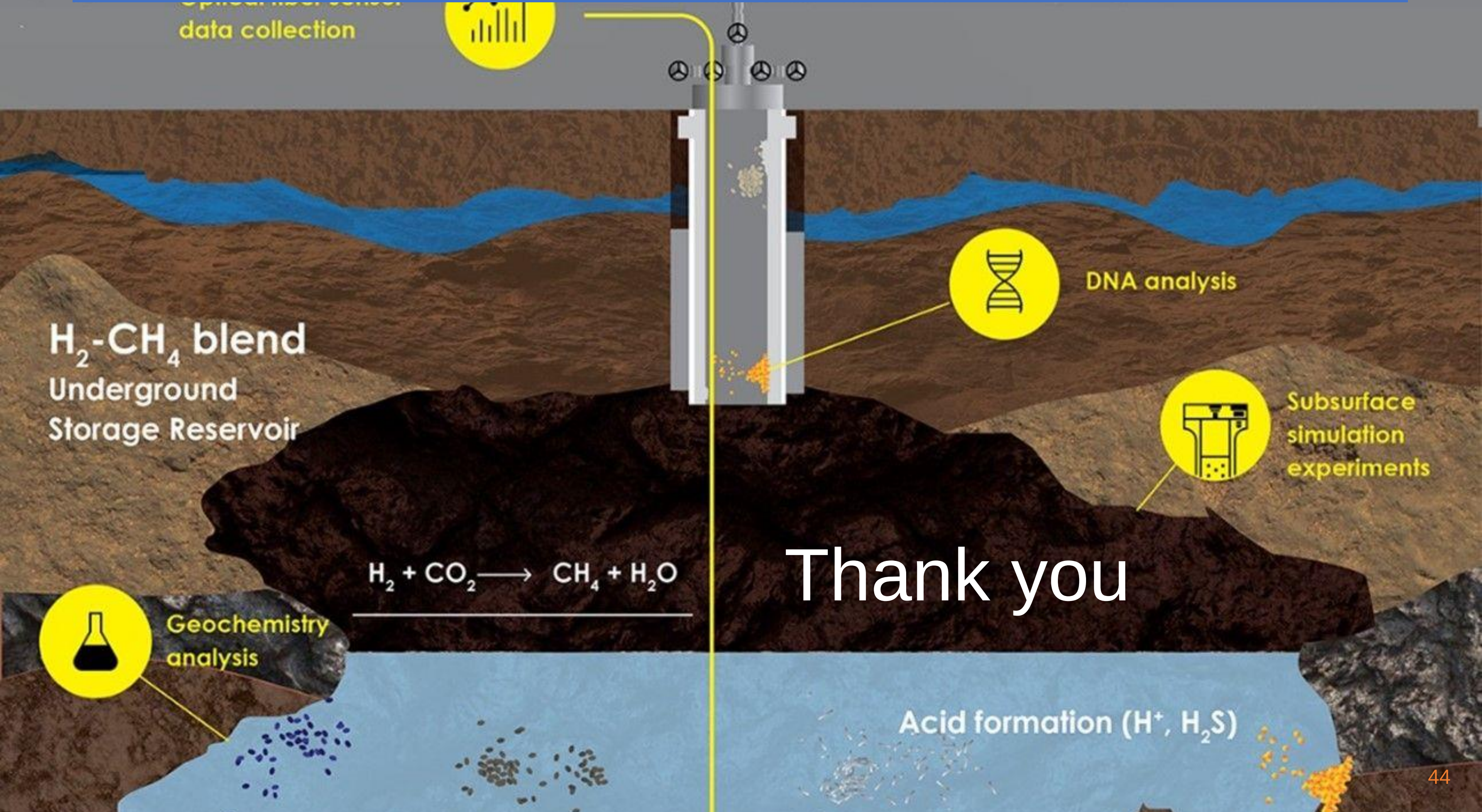
Casing arrival appears as regular bands while the formation arrivals are usually irregular

CBL-VDL GUIDELINES

CBL Bonding Type	Amplitude	Casing Arrival	Formation Arrival
Free Pipe	High	Strong	Very Weak
Good bond Casing to Cement	Low	Weak	Strong
Good Bond-Casing to Formation	Low	Weak	Strong
Good Casing Bond but poor Formation Bond	Low	Weak	Very Weak
Microannulus	High	Medium	Medium
Fast Formation	High	Swamped by Formation signal	Strong

Haggag, M., 2024

END OF LECTURE



Thank you